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THE SCATTERED LIGHT COMPARATIVE BEAM ANEMOMETER. A LASER ANEMOMETER FOR THE MEASUREMENT OF THREE VELOCITY COMPONENTS

W.J. Hiller and G.E.A. Meier

Translation of "Das Streulichtvergleichsstrahlanemometer, ein Laseranemometer zur Messung von drei Geschwindigkeitskomponenten," Max-Planck-Institut für Strömungsforuchung, Göttingen (West Ger.), Report 3/1972, July 1972, 32 pp.

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16. Abstract

The self-aligning reference beam method for simultaneous measurement of three components of flow velocity is described. The characteristic features of this method consist in that both the reference beam and the object beam are produced by scattering and that the interference takes place in concentric wave systems. Velocity measurements using this method in water and air flows with He, Ne and argon lasers as light sources and photodiodes as photodetectors are described.

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THE SCATTERED LIGHT COMPARATIVE BEAM ANEMOMETER. A LASER ANEMOMETER FOR THE MEASUREMENT OF THREE VELOCITY COMPONENTS

W.J. Hiller and G.E.A. Meier

1. Introduction /1*

The optical anemometers known to date are employed almost exclusively for measuring one velocity component. Expansion of the conventional setups based on the crossed beam and reference beam methods to the measurement of three velocity components involves considerable technical outlay. This is partly because the setups based on the classical concepts of interference optics contain many mirrors, beam splitters and other elements requiring adjustment, the structure of which places appreciable demands on the experimenter's patience and skill, even in a unidimensional setup. If we attempt to expand these systems to the measurement of three velocity components, we find ourselves faced with serious technical problems.

The goal of the developmental work described below was thus to make the measurement of three velocity components possible in a setup which was as simple as possible and uncritical in structure.

2. The Principle of the Scattered Light Reference Beam Anemometer

The concept of the scattered light reference beam anemometer is based on the following principal ideas: In all laser anemometers, the Doppler shift in light scattered by an object, generally located at the laser beam focus, is used to measure the object's velocity. In a reference beam anemometer, the Doppler

* Numbers in the margin indicate pagination in the foreign text.

shift is obtained by determining the frequency difference between /2
scattered and unscattered light. In the case of coherent scattering, however, the frequency of the unscattered laser light is also retained by that light which is scattered on nonmoving objects. It is therefore possible to also produce the reference beam by scattering. If we likewise place the scattering structure used for this purpose at a focal point of the laser beam, we obtain concentric wave systems which produce easily evaluated interference patterns on spherical surfaces.

2.1. The Simple Basic Setup

A simple setup which covers the basic ideas is drawn in Fig. 1. The light beam generated by laser L is focused by lens L1 with aperture angle δ on scattering plate S. The character of this scattering plate S is variable within wide limits. Is extends from pure phase structures, e.g. the optical inhomogeneities of a sheet or foil, over mixed cases, to pure amplitude struc- /3
tures, e.g. photosensitive films, and more or less regular grating structures or even apertured sheets and individual particles on a low-disturbance carrier. Scattered light with an aperature angle β is focused on the object, along with the unscattered component of the laser light, by lens L_2. The optical inhomogeneity of scattering center S is adjusted so that the intensity of the scattered light impinging upon the object at aperture angle γ amounts to a total of only about 1% of the as yet unscattered laser light. From moving object O, scattered light is again propagated, upon which the scattered light from screen S is superimposed in the half-space behind the plane of the object. The light originating from this last-mentioned scattered light through interaction with the scattering particles within the volume measured, scattered a second time, plays no role because of its low intensity.

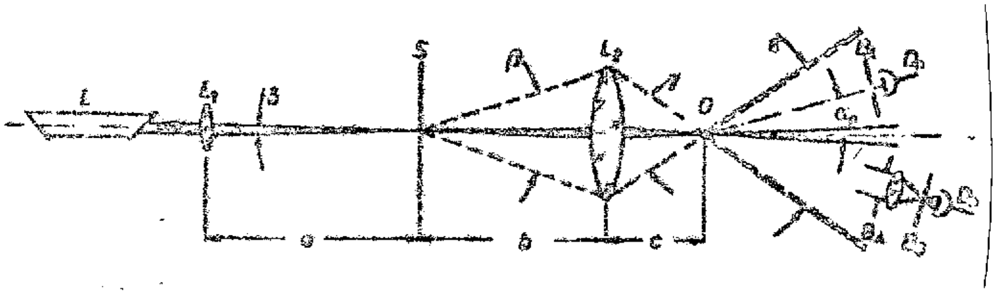

Fig. 1. Basic setup of scattered light reference beam anemometer.

Three diodes D_n are now set up at angles α_n relative to the laser beam axis in order to measure three linearly independent components of scattering particle velocity. In order that the measurements yield linearly independent velocity components, the three angles α_1 to α_3 must not lie in a common plane.

The Doppler shift frequency produced at the diodes by the mixing of reference beam light and scattered light from the object is, as in all reference beam methods, directly proportional to the projection of the velocity $\tilde{v}$ to be measured onto the perpendicular to the bisector of α_n which lies in the plane spanned by the vectors subtending α_n. Further details regarding evaluation of the frequency shifts will be covered in Section 4 of this report.

2.2. Interchange of Object and Scattering Center /4

Since points S and O in the scattered light reference beam anemometer shown in Fig. 1 are both scattering centers whose action is essentially equivalent, we can interchange the sequence of the object and reference beam generator without impairing the effectiveness of the method. Such a setup is shown in Fig. 2. Diameter D_1 of the parallel beam leaving laser L is increased to diameter D_2 here by a telescope with lens L_1, space filter R and lens L_2 and is focused on objected O by lens L_3 at aperture angle δ. The scattered light from the moving object received by

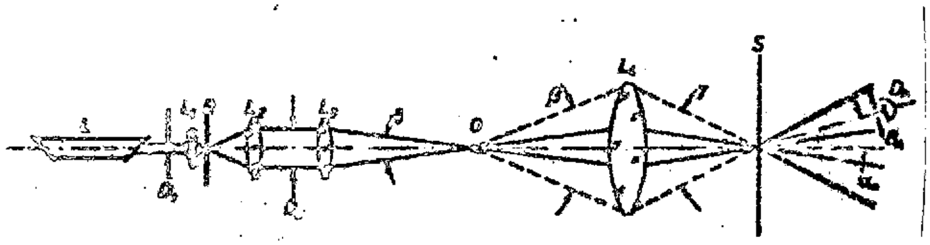

Fig. 2. Scattered light reference beam anemometer with interchanged object and scattering center.

lens L_4 at aperture angle β is now focused on scattering center S at aperture angle γ along with the unscattered laser light. The unscattered laser light, with its high intensity relative to the scattered light propagating from O, now generates an additional beam of scattered light at scattering center S, whose character -- as mentioned above -- is variable within wide limits; the beam, indicated in the figure with dotted lines, again has the beam of scattered light propagating from O superimposed upon it in the half-space behind scattering center S. The Doppler frequency differences are now produced by mixing at photocells D_n set up at angles α_n. Through the selection of arbitrary angles α_n, we also determine the magnitude of the frequencies produced. For small α_n, i.e. close to the optical axis or the original axis of the laser beam, the resultant Doppler frequency differences are small. /5

2.3. Directional Uncertainty and Superposition of Velocities

A serious shortcoming of all laser anemometers used to date is that the sign of the velocity component to be measured very accurately by means of the Doppler frequency difference is unknown. The reason is that a Doppler shift of given size produced at object O -- regardless of whether it generates higher or lower frequencies in the resultant scattered light -- produces the same frequency difference upon mixing with the original laser light, without frequency shift, at diodes D_n, and its sign cannot

be determined. This basic difficulty can be eliminated by imparting an additional, known frequency shift to the reference beam in the reference beam method. The production of such a frequency shift in laser light is a very involved technical problem in the conventional reference beam methods and can be solved less than satisfactorily by the various types of modulators and other electrooptical systems. Since the reference beam is produced by scattering in our scattered light reference beam anemometer, it is useful to produce the frequency shift in the reference beam by moving the scattering centers used to produce the reference /6
beam in the same way the frequency shift is produced in the light at the object. Fig. 3 shows such a setup. The setup used in Fig. 2 is modified in that scattering center S takes the form of a rotating disk here. The reference beam frequency shifts can be varied by selecting different points on the radius of the disk, just as they can be varied by varying the disk's angular frequency. Thus a constant frequency f_n is now produced at each photocell D_n if the scattering particles in the object are at rest. Movement of the scattering objects raises or lowers this frequency f_n, depending upon the sign of the velocity component. If the signs of the individual velocity components are known, the sign of the principal flow can also be determined directly. The big problem in determining the direction of the velocity vector -- if the signs of the components are unknown, they can be combined in 2^3 ways to form a resultant -- is eliminated by very /7
simple means.

In Fig. 3, a diaphragm B is set up behind scattering disk S to mask the laser beam, no longer needed in the receiving system, and a lens L_5 is put in to focus the scattered light on a field stop B_G; the individual photocells D_n have an aperture stop B_A, which is important for signal quality in a reference beam method.

The method described for shifting the frequency of the reference beam permits an interesting variant in the application

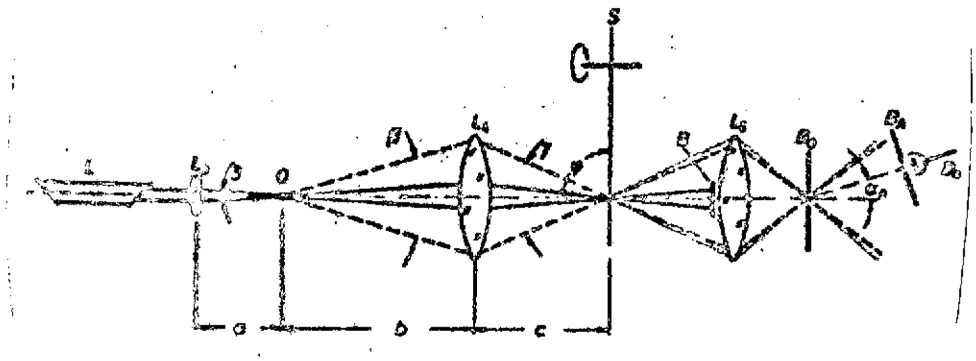

Fig. 3. Scattered light reference beam anemometer with reference beam frequency shift.

of laser anemometers, particularly for the measurement of steady velocities. If the velocity vector of the scattering particles at S which generate the reference beam is made to equal the velocity vector of the scattering particles at O in direction (negative sign!) and magnitude, we obtain a frequency of zero at photodetectors D_n. This means that the laser anemometer can be used in a type of null method for determining the velocity of an object structure at O, the direction and magnitude of velocity being obtained immediately from the direction and magnitude of the velocity of S. Not just rotating disks, but also moving tapes, flows or the like are of course suitable for this scattering center S. If the movement of scattering particles at O is nonsteady, e.g. in turbulent flows, the principal flow velocity can still be separated from the perturbations with this null method. By changing object distance b relative to the distance c between the scattering center and lens L_4, we can also perform a transformation of object particle and scattering particle velocities.

A technical variant of the setup shown in Fig. 3 results if /8
scattering center S is designed not as a transparent object but as a mirror which, say, can be set at a variable angle relative to the optical axis. The subsequent elements, up to the photodetector, must then of course be relocated as a function of the angle of reflection.

3. Designs for the Scattered Light Reference Beam Anemometer

A few additional versions of the scattered light reference beam anemometer and several variants in terms of design and mode of functioning will now be discussed. Details can only be discussed in terms of examples in each case; it is obvious that improvements for this or that application can also be achieved by combining the basic setups discussed.

3.1. Integrated Measurement and Observation System

Since the apparatus consists of two parts in the scattered light reference beam anemometer setups covered so far, namely the illumination device, on the one hand, with the focusing optics and in some cases the scattering center with an additional focusing lens, and, on the other, a pickup system with the photodetectors to be used, which can also contain the scattering center, however, if the object and scattering center are interchanged, it is useful to combine the two units, which will be referred to here as the illumination unit and the receiving unit /9
for brevity, into a single instrument in each case. Fig. 4 shows a setup with a receiving unit which at the same time contains a measurement and observation system.

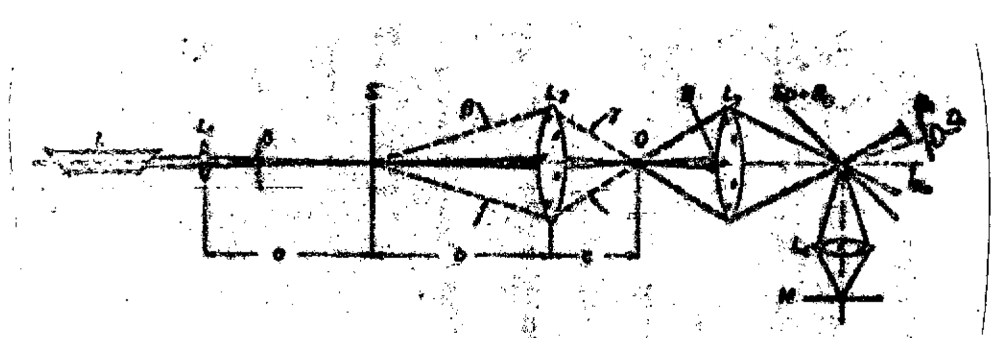

Fig. 4. Scattered light reference beam anemometer with integrated measurement and observation system.

A mirror inclined with respect to the optical axis and fitted with an aperture serves, on the one hand, as a field stop for the scattered light component directed at photodiodes D_n and, on the other hand, as a means of reflecting all remaining light onto a matte disk M, on which an image of the vicinity of the focus or object point O is produced if the receiving system is set up correctly. This setup makes it simple to adjust very small field stop B_G optimally. In principle, an ocular could also be used in place of matte plate M. We consider this arrangement to be too dangerous when lasers with light outputs of more than 1 mW are used, however. Movable stop B, perpendicular to the optical axis, is used to mask the unscattered laser light.

The entire setup can of course also be bent at point O. If scattering center S is located in front of the object -- as shown here in Fig. 4 -- the angle of the bend can be made so large that the unscattered laser beam passes lens L_3, and stop B can also be omitted. In this case it is only important that scattered light from S and O enter lens L_3 superimposed. /10

If the scattering center and object are interchanged, it is important that the unscattered laser light still passes through lens L_3, so scattered light for the reference beam can be produced approximately at the position of field stop B_G.

3.2. Measurement of Three Velocity Components with Only One Photodetector

In many applications for the anemometer, it is known prior to the experiment that the Doppler frequency differences to be expected for the various velocity components lie within a quite specific, well-defined region or can be shifted into a desirable region by means of a specific arrangement of diodes. If it is possible to give the three frequencies distinctly different values about whose configuration and sequence no doubt can arise, the measuring equipment can be highly simplified if the three signals are delivered by a single photodetector. The setup necessary for this is shown in Fig. 5. Only the scattered light at angle α_1 directly impinges upon the photodetector shown. The scattered light to be observed at α_2 and α_3 is directed to the photodetector by means of deflecting mirrors.

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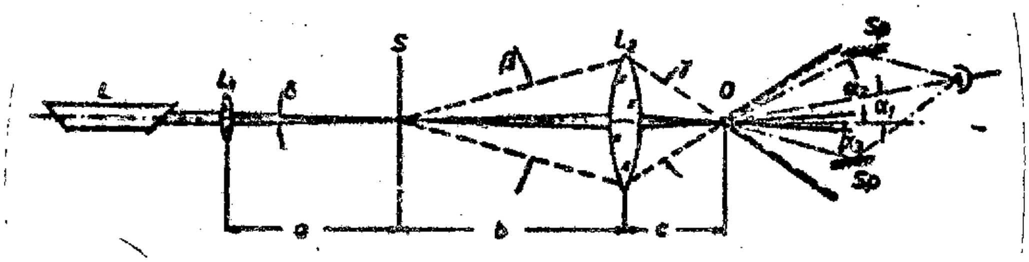

Fig. 5. Three-dimensional scattered light reference beam anemometer with only one photodetector.

For this application, variants are of course likewise conceivable which might for example have the light to be mixed led from the reception points to the photodetector via light guides.

3.3. Application of the Method to Back Scatter

Although back scatter is not utilized in most applications of laser anemometry because the intensity of the back-scattered light amounts to only about 1% of the intensity of light scattered forward by the particles normally present and the use of back scatter thus becomes simply a question of laser power and the load capacity of the measurement object, it is nevertheless important to have a scattered light reference beam anemometer for back scatter available for certain applications of the method in which either the object space is accessible from only one side or sufficient scattering intensities are achieved in back scatter. The setup to be used for this is shown in Fig. 6. Technically, this variant is of particular interest because all optical and mechanical components up to the photodetectors can be combined in one instrument which, as a permanently adjusted unit, need only have the focus of the exiting laser beam be brought up to the object of measurement.

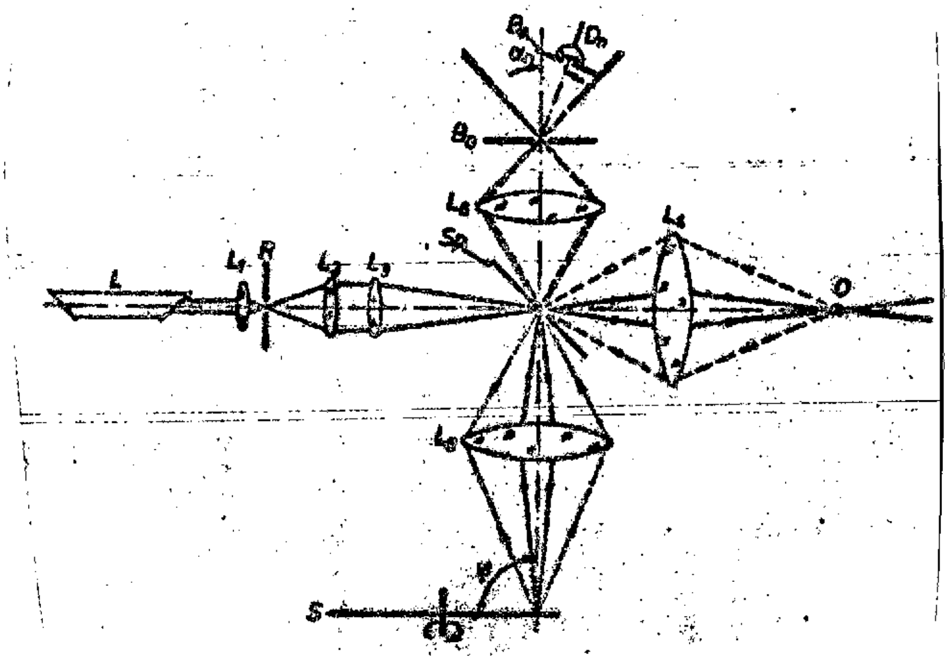

Fig. 6. Scattered light reference beam anemometer for back scatter.

As one can easily see, the setup shown in Fig. 6 is quite similar to that of a Michelson interferometer. The difference, from the optical point of view, is merely that parallel beam interference patterns are not generated here in the receiving arm of the interferometer, but rather that interference patterns of spherical waves are involved which propagate from points O and S. The beam coming from laser L is expanded via lens L_1 and L_2 and focused by lens L_3 on a beam-splitting mirror Sp. The mirror, which it is desirable to design in the form of a very thin foil or glass plate in order to avoid disruptive parallel plate interference figures, reflects approximately 10% of the laser beam power onto lens L_5, which focuses the beam on scattering center S. /13

This scattering center can of course, as outlined earlier, be designed in the form of a moving center and is now given a surface which is optimum for back scatter. The back-scattered light, serving as a reference beam, is in turn focused on mirror Sp by lens L_5, through which 90% of it passes, thereby reaching the receiving arm of the interferometer. The mirror is penetrated by 90% of the power of the laser beam focused on mirror Sp by lens L_3, which is focused on object point O by lens L_4, which in this setup would be equivalent to L_5 in focal length, diameter and distance from mirror Sp for reasons of eikonal equivalence and aperture angle equivalence. The back-scattered, Doppler-shifted signal from O is in turn focused on mirror Sp, and now likewise only 10% unfortunately is reflected into the receiving beam path. Here it has the scattered light produced by S superimposed upon it in the manner discussed earlier and is directed at the photodetectors. An apparent shortcoming of this basic setup is that a large portion of the light scattered by the object is lost upon reflection at mirror Sp. This is meant to be eliminated by the setup shown in Fig. 7. In this arrangement, which is simplified to a relatively high degree and nevertheless represents an improvement, the laser light is focused by lens L_1,L_2 directly onto object O through an only weakly reflecting /14
inner section of mirror Sp. The scattered light is reflected by the relatively highly reflective section of mirror Sp onto lens L_4 and is directed at field stop B_G by this lens. Behind it is again the familiar arrangement of photodetectors. About 10% of the laser light is reflected onto scattering center S by the weakly reflecting portion of mirror Sp. Ten percent of the in- /15
tensity of the reference beam from S passes through mirror Sp and reaches the field stop along with the scattered light from object O. The intensity of the reference beam is sufficient in spite of pronounced attenuation by mirror Sp, due to the high back-scattering power of S.

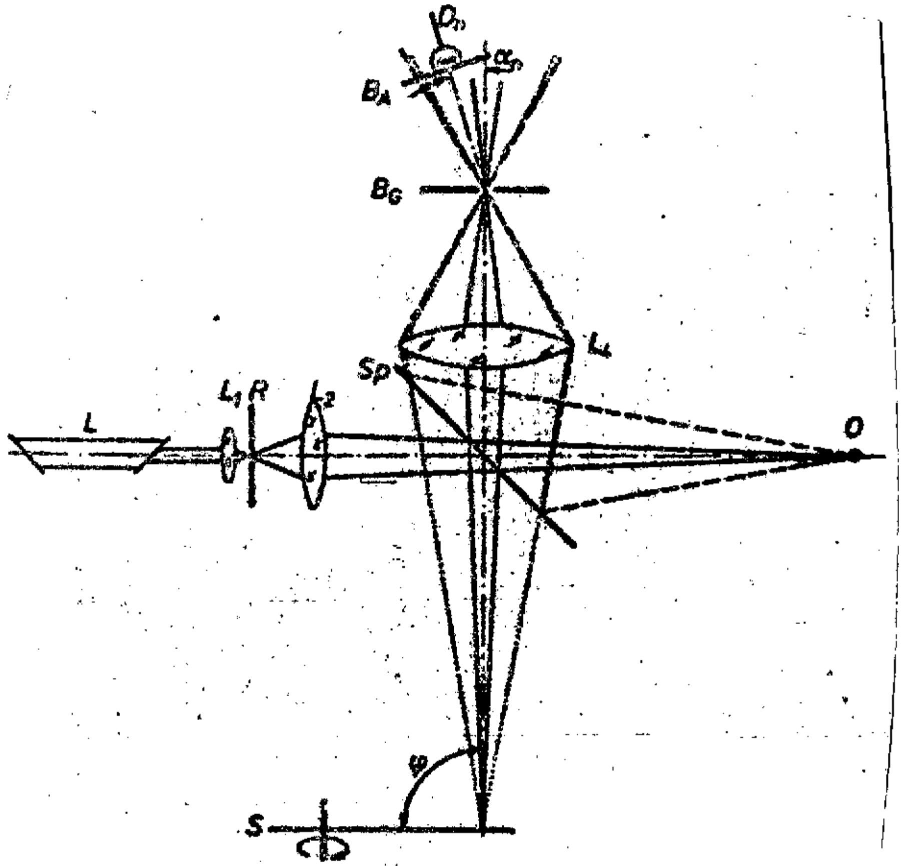

Fig. 7. Simple back scatter anemometer.

This setup also has a variant in which scattering center S can also be shifted to the position of field stop B_G and a fully reflecting mirror can be inserted at S so that the partial beam of laser light can be reflected against itself and once more pass through the partially reflecting area of mirror Sp. The beam is focused by lens L_4 on field stop B_G, which can then perform the function of the scattering center. The eikonal condition is also satisfied by this setup, so low-order interference figures are used here, too, to produce the Doppler difference signals.

If we now also interchange the location of the above-mentioned mirror with that of object O, we obtain the setup shown in Fig. 8. Here, the primary laser beam is directed at the object by an almost completely reflecting deflecting mirror Sp, and the scattered light produced there is picked up around this mirror Sp by lens L_4 and directed toward the receiving unit behind. The small component of the laser light which passes through mirror Sp is back-reflected at fully reflecting mirror Sp_1 and is likewise reflected into the receiving unit from the back side of mirror Sp. The focusing at scattering center S by lens L_4 still yields relatively high intensities here, which are used to generate the reference beam scattered light.

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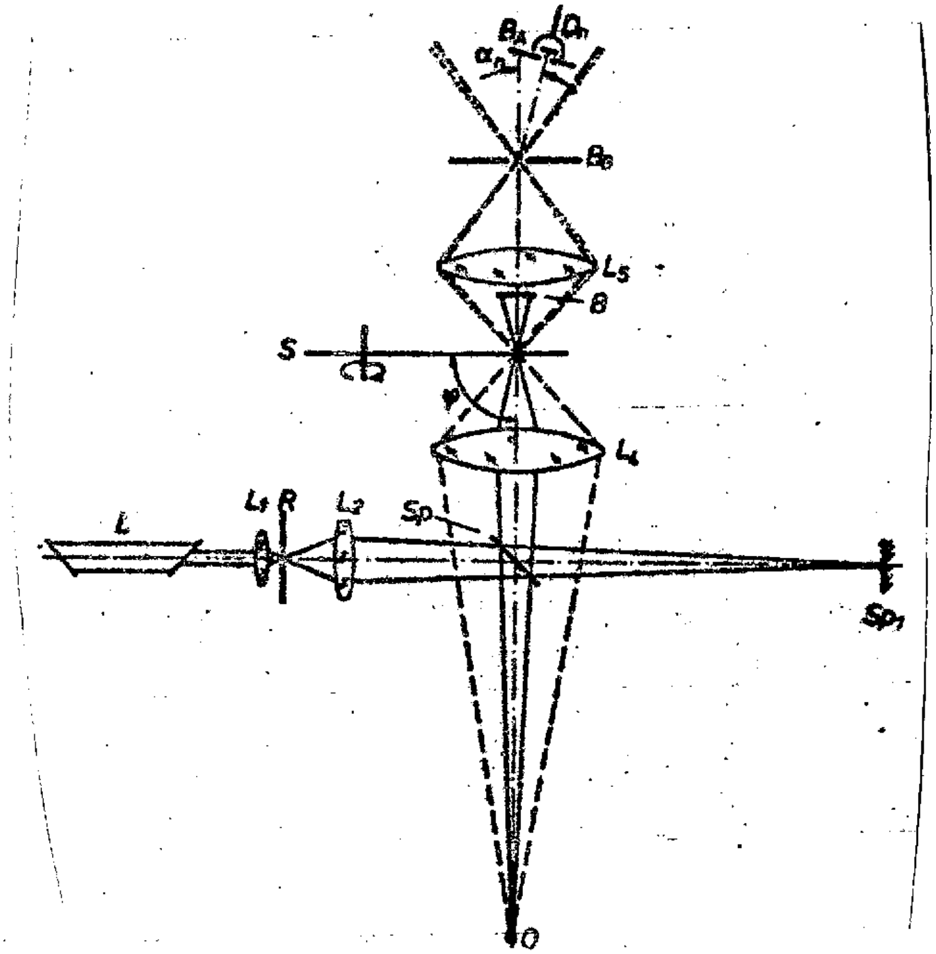

Fig. 8. Back scatter anemometer with reference beam generated at receiving unit.

This setup, too, permits several variations which primarily serve the purpose of additional technical simplification. Thus mirror Sp might be set up on the other side of lens L_4, in which case lens L_2 must be shifted past partially reflecting mirror Sp toward partially reflecting mirror Sp_1 and the corresponding adjustment made in focal length.

3.4. Comparison of the Velocities of Two Objects /17

Since, as indicated earlier, the production of scattered light at object O differs in no way from scattered light production at scattering center S, it is reasonable to apply this method to a comparison of the velocities of different objects. The setup for this, shown in Fig. 9, corresponds in practical terms to the basic anemometer configuration. Thus an additional object of unknown velocity is merely placed at the position of scattering center S.

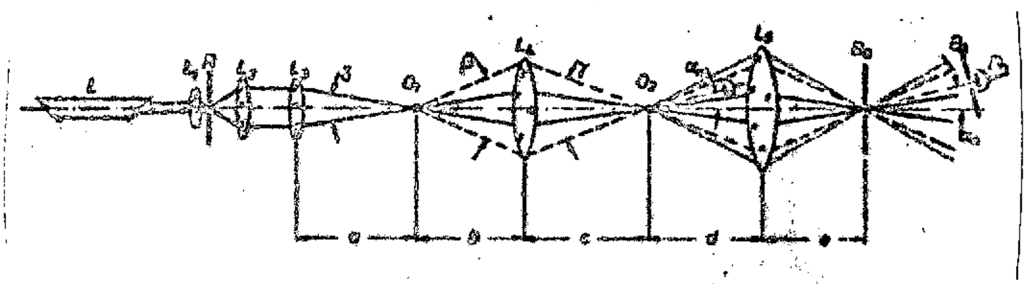

Fig. 9. Application of the scattered light method to the comparison of velocities of two objects in spatially separate locations.

The laser beam focused at object O_1 by lens L_3 is focused a second time by lens L_4, along with the scattered light produced at O_1, on an object O_2. While the scattered light from O_1 passes through object O_2 with relatively little disturbance, the laser light produces more scattered light at O_2, which is superimposed on the scattered light first produced at O_1 and can be collected with photodetectors D_n in the half-space behind O_2. Further /18 imaging with L_5 and the subsequent elements serves merely to improve reception quality. The Doppler frequency differences picked up by the photocells represent the difference in the velocity components of scattering particles at O_1 and O_2, although care must be taken to see that the velocities are transformed in the ratio of image distance B to object distance C.

If it should be useful for some reason, the production of scattered light can be repeated any number of times, although a mixture of different object velocities would then occur which under some circumstances would be difficult to disentangle.

A variant of this method, shown in Fig. 10, thus appears to be more significant.

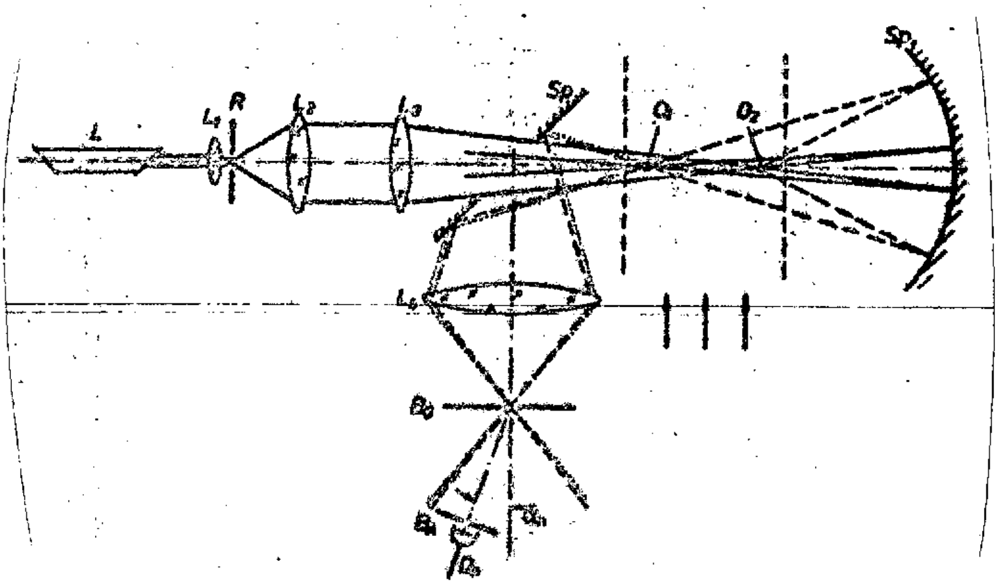

Fig. 10. Comparison of velocities at two object positions.

A frequently encountered task is that of comparing the velocities of two object points which are located in a wind tunnel or in a system which is closed to the outside spatially. /19

Since it is often not possible here to produce further imaging by means of a lens, it can be achieved in the "folded" beam path by means of a mirror outside the system.

Imaging with concave mirror Sp_1 can be used to compare the velocities of adjacent object points O_1 and O_2. Deflecting mirror Sp has an opening at the center which first allows the laser light to pass through, on the one hand, to illuminate object point O_1 and which, on the other, allows the reflected laser beam to pass through again toward the light source. Scattered light from O_1 and O_2 is deflected by mirror Sp into the receiving unit, already referred to frequently above.

An interesting variant of the scattered light method is obtained if we wish to compare the velocities of very closely neighboring objects. It is then possible to bring both objects into a focal point of the setup and thereby generate object scattered light and a reference beam at one focal point. Fig. 11 shows a setup such as would be used, say, to measure the slip speed of transparent objects sliding over one another. The il- /20 lumination unit focuses the laser light at aperture angle δ on the interface between the neighboring objects, and scattered light propagates from the two. Thus two cones of scattered light are generated which exhibit Doppler shifts relative to the illumination frequency, depending upon object velocity. A receiving device along the lines of the instruments described above superimposes the two cones of scattered light at photodetectors D_n. Frequently, only two photodetectors are necessary with this method, since mechanical relationships permit only a two-dimensional multiplicity of velocities.

We obtain a particularly simple anemometer setup for back scatter here; this case is of particular interest in that, in contrast to liquids and gases, back scatter can be much stronger

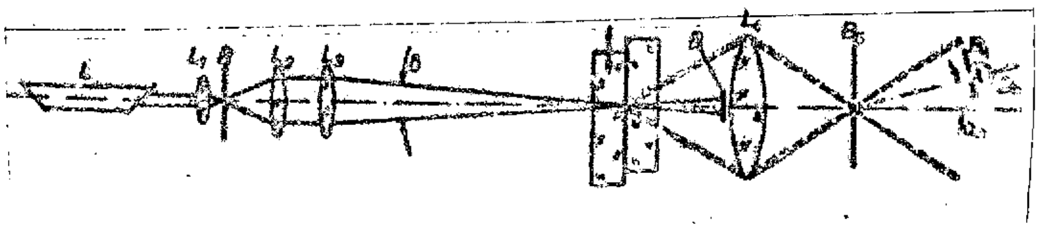

Fig. 11. Application of the scattered light reference beam method to the measurement of velocities of neighboring objects for forward scattering.

than forward scatter at the interfaces between solids. Such a setup is shown in Fig. 12.

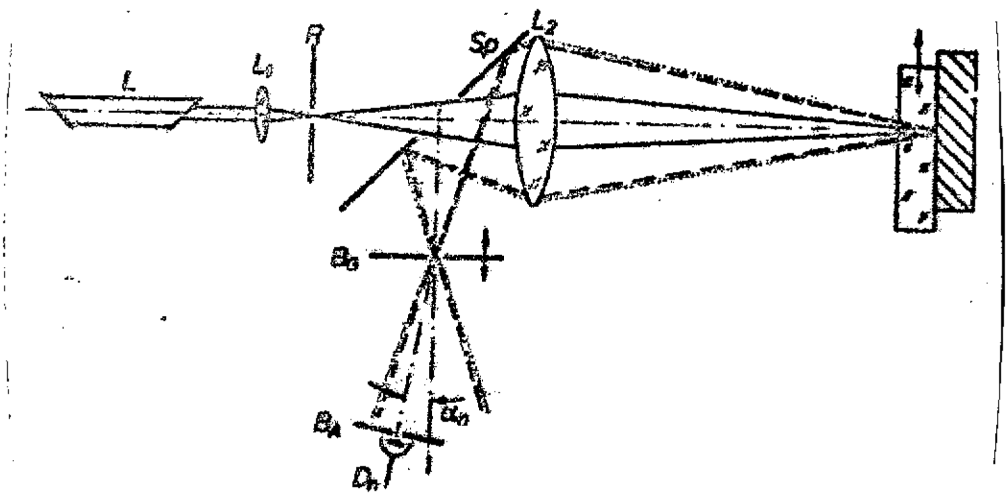

Fig. 12. Application of the scattered light reference beam method to the measurement of velocities of neighboring objects for back scatter.

The beam coming from laser L is widened by lens L_1 and, after /21 passing through space filter R, is focused by lens L_2 on the object at the interface between the two media, the first of which must be of adequate optical quality here, while the second may be completely opaque. The scattered light propagating from the interface between the media, part of which exhibits the Doppler shift corresponding to the velocity of one medium and part of which exhibits the Doppler shift corresponding to the velocity of the second, is focused on field stop B_G by lens L_2 and deflecting mirror Sp and, after passing through this stop, is directed toward the familiar receiving device, containing two or perhaps even three photodetectors.

3.5. Application of the Difference Method

The difference method which we developed in collaboration with H. Bossel [2] can also be used with the scattered light reference beam anemometer to suppress signal interference. The difference method is based on the fact that if the light components to be superimposed have different linear polarization, they can be superimposed in such a manner -- by splitting them as a function of polarization, e.g. with a Wollaston prism -- that the resultant interference figures exhibit a phase shift. /22
This makes it possible to obtain Doppler frequency difference signals as differences in the electrical output voltages of two photodiodes, so that all other signals, not attributable to correspondingly polarized light, produce no signal in this circuit. In practical terms, this means that all interference which enters the receiving unit from optical sources is eliminated by the setup. One of the many possible configurations is shown in Fig. 13 as a sample application of the difference method.

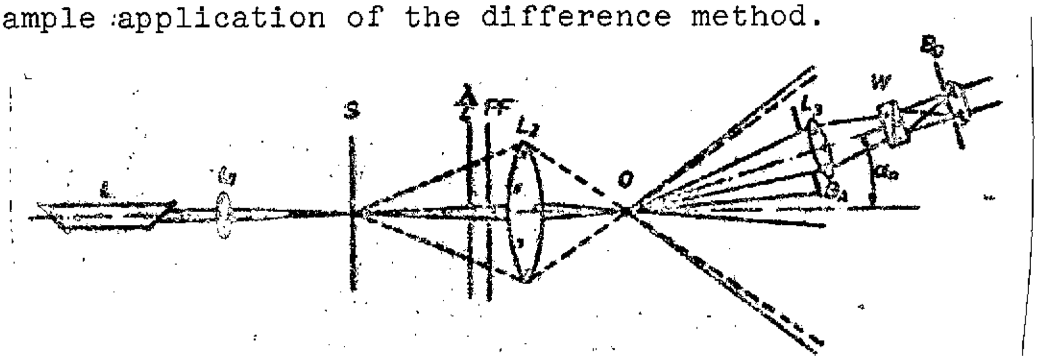

Fig. 13. Scattered light reference beam anemometer applying the difference method.

The light leaving laser L, generally linearly polarized, is focused on a scattering center S by lens L_1. The unscattered laser light passes through a filter arrangement via suitable holes and is focused at object O with lens L_2, maintaining its original direction of polarization, and produces the object scattered light there. The reference scattered light propagating from S is rotated 90° in polarization relative to the original direction of /23 laser light polarization with the aid of a $\lambda/4$ film and a polarization filter. The scattered light likewise focused on O by lens L_2 now has an orthogonal polarization relative to the laser light and, correspondingly, also an approximately orthogonal polarization relative to the scattered light generated at O. The pickup system, operating at angle α_n, thus receives two orthogonally polarized scattered light components, which it resolves with a Wollaston prism in the manner described above, adds them at the two photocells, and transforms them into two opposed-phase mix products.

4. Evaluation of Doppler Difference Measurements

The optical anemometer utilizes the Doppler effect to determine velocity. To illustrate the situation, we imagine an observer B at rest at the origin of rectangular coordinate system S (Fig. 14). Let light source L', assumed to move at constant /24 velocity v parallel to the x-axis, emit light of frequency $\nu_{L'}$ -- relative to a system linked to the light source -- which reaches observer B in the form of a plane wave with propagation direction n_{St}. The Doppler frequency ν_D measured by B is then:

$$\nu_D = \nu_{L'} \frac{\sqrt{1 - \frac{v^2}{c^2}}}{1 - \frac{v}{c} n_{St_x}} \quad (1)$$

where n_{St_x} is the projection of unit vector n_{St} on the x-axis and c is the velocity of light (in vacuo).

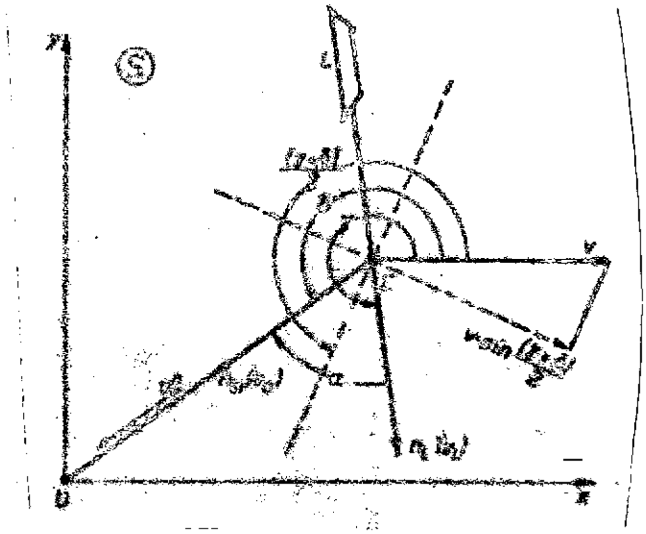

Fig. 14. Principle of the method.

In the optical anemometer, light source L' takes the form of a small particle of velocity v which is irradiated by a monochromatic, coherent light source L((laser) at rest in system S and emits this light as a secondary radiator. It is assumed here that the frequency $\nu_{L'}$ of the light emitted by the scattering particle is the same as the excitation frequency (relative to a system of coordinates fixed with respect to the scattering particle). If we use ν_L to designate the frequency of the light emitted by the quiescent light source L in direction n_L, then

$$\nu_L' = \nu_L \frac{1 - \frac{v}{c} n_{Lx}}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{2}$$

where n_{Lx} is the projection of unit vector n_L on the x-axis. From (1) and (2) it follows that

$$\nu_D = \nu_L \frac{1 - \frac{v}{c} n_{Lx}}{1 - \frac{v}{c} n_{Stx}} \tag{3}$$

Thus the velocity v of the scattering particle can be determined from measured frequency ν_D and parameters ν_L, n_{Lx}, n_{Stx}. However, /25

ν_D can frequently not be measured directly with the desired accuracy, since in many practical cases, ν_D/ν_L is on the same order of magnitude as the resolution of spectral apparatus presently available.

We therefore reduce the determination of Doppler frequency ν_D to the measurement of its deviation from a known frequency (e.g. ν_L'). These measurements can be made quite easily, since photodetectors have the property that when irradiated with light of different frequencies, they transmit an electrical signal whose frequency is equal in magnitude to the frequency difference in the light signals. If we take ν_L itself as the reference frequency, we obtain the following for Doppler shift frequency ν_{DV}:

$$\nu_{DV} = |\nu_L - \nu_D| = \left|\nu_L \frac{v}{c} \frac{n_{Stx} - n_{Lx}}{1 - \frac{v}{c} n_{Stx}}\right|$$

In laser anemometry practice, $v \ll c$ always holds, so the term $(v/c)n_{Stx}$ in the numerator can be neglected. (E.g., for $v = 10^3$ $= 10^3$ m/sec, $n_{Stx} = 1$, $c = 3 \cdot 10^8$ m/sec, the error in ν_{DV} is about $3 \cdot 10^4$%.) In the form

$$\nu_{DV} = \left|\nu_L \frac{v}{c} (n_{Stx} - n_{Lx})\right|$$

ν_{DV} is directly proportional to the magnitude of v for otherwise constant operating parameters.

Generation of the frequency difference by mixing at a photodetector is thus an important condition for applicability of the optical Doppler effect to velocity determination.

If we use γ and δ to designate the angles between the x-axis and n_L and the x-axis and n_{St}, respectively, then

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$$\nu_{DV} = \left| \nu_L \frac{2v}{c} \sin\frac{\gamma+\delta}{2} \cdot \sin\frac{\gamma-\delta}{2} \right| \qquad (4)$$

In this form, equation (4) can be interpreted in a manner independent of the special coordinate system (Fig. 14):

Only the projection of v on the bisector of the complement of $(\gamma + \delta)/2$ contributes to $_{DV}$. The factor $|\sin(\gamma - \delta)/2|$, which is independent of the choice of coordinate system, can be interpreted as an effect of the geometry of the configuration. The smaller the angle between n_{ST} and n_L, the smaller the Doppler shift ν_{DV}.

If we begin with the obvious approach of measuring the angles from n_L and designate angle $\delta - \gamma$ as α (observation angle), that component v_α of v is then measured in magnitude which is obtained as the projection on the bisector of the complement of $\alpha/2$. Then

$$v_\alpha = \frac{\lambda_L \nu_{DV}}{2} \frac{1}{|\sin\frac{\alpha}{2}|}$$

Three measurements of v_{α_n} in three linearly independent directions n_{St_n} (n = 1,2,3) are necessary for a complete determination of velocity vector v. Since, as mentioned above, only the magnitudes are measured, these three components v_{α_n} can be combined in a total of 2^3 ways to obtain a resultant $\bar{v}$. Although in some cases it is possible to combine the components unequivocally (e.g. when the direction of motion is known approximately), other approaches must be taken for a general solution to this problem.

One possibility for determining the signs of the velocity components is obtained if Doppler frequency ν_D obtained from equation (3) is not mixed with the frequency ν_L of the laser /27 light itself at the diode, but with one shifted toward it by $\Delta\nu$. At particle velocity $v = 0$, a frequency of $\nu_{DV} = |\nu_L - (\nu_L + \Delta\nu)| = |\Delta\nu|$ is then observed at the diode output. The sign of the velocity component is now established unequivocally for the frequency range $\nu_L - \Delta\nu \leq \nu_D \leq \nu_L + \Delta\nu$. This condition must of course be satisfied simultaneously at all photodetectors.

The actual purpose for which an optical anemometer is used is not primarily to determine the velocity of an individual light-scattering particle; rather, we would like to use the velocity of scattering particles which we imagine to be embedded in a gas or liquid and carried along by it to determine the velocity of flow itself.

For this purpose, it must first be ensured that the scattering particles are carried along by the flow without slippage. This is more likely to be the case the smaller the particles are, the closer their specific gravity is to that of the flowing medium to be studied, and the lower the velocity gradients are within the flow. If we disregard extremely nonsteady flows such as ultrasonic vibrations, the passage of scattering particles through compression waves, and highly dilute gases, we can usually find suitable light-scattering particles.

Another requirement is that the measured values come from a volume element in which velocity is practically constant and that the measured values -- particularly in the case of nonsteady flows -- are delivered continuously by the measurement apparatus. Without going into details, let us just mention that an arbitrarily small measurement volume is not feasible, due to un- /28
avoidable diffraction phenomena; moreover, when measurement volume is reduced, the dwell time of scattering particles and thus the number of oscillations available for analysis is reduced; this amounts to deterioration in velocity resolution. The

three-dimensional resolution of an optical anemometer is established by the choice of aperture and field stops and by laser beam focusing.

The important advantages of optical anemometers are considered to be the facts that flow is not affected by measurement and calibration is unnecessary.

5. Experiments

The velocity measurements were performed on flows of water and air. While a sufficient number of light-scattering particles still remained in tap water which had been sent through a filter of 0.6 μm pore size, it was found to be desirable to add particles to air in the form of tiny water droplets in order to increase the intensity of scattered light.

An He-Ne laser (0.5 W) and an argon laser (5 W) were used selectively as light sources. Photodiodes (BPX65 or PIN 6 LC) with an effective area of 1 and 7 mm^2, respectively, were used as photodetectors.

The photodiodes were mounted on a flat panel at the corners /29 of an equilateral triangle with edges of 17 mm. This panel was set up at a distance of 200 mm from measurement point O (Fig. 1) in such a manner that the undeflected laser beam impinged on the panel perpendicularly at the center of the triangle. In this adjustment position, the angles of observation are about 6°.

Fig. 15 shows three oscillograms of the voltages produced by the diodes in the study of a completely turbulent flow of water in a flat tunnel with a depth of 1 cm. At this point, we should point out a difficulty involved in the scattered light reference beam method which always occurs if measurement point O (Fig. 1)

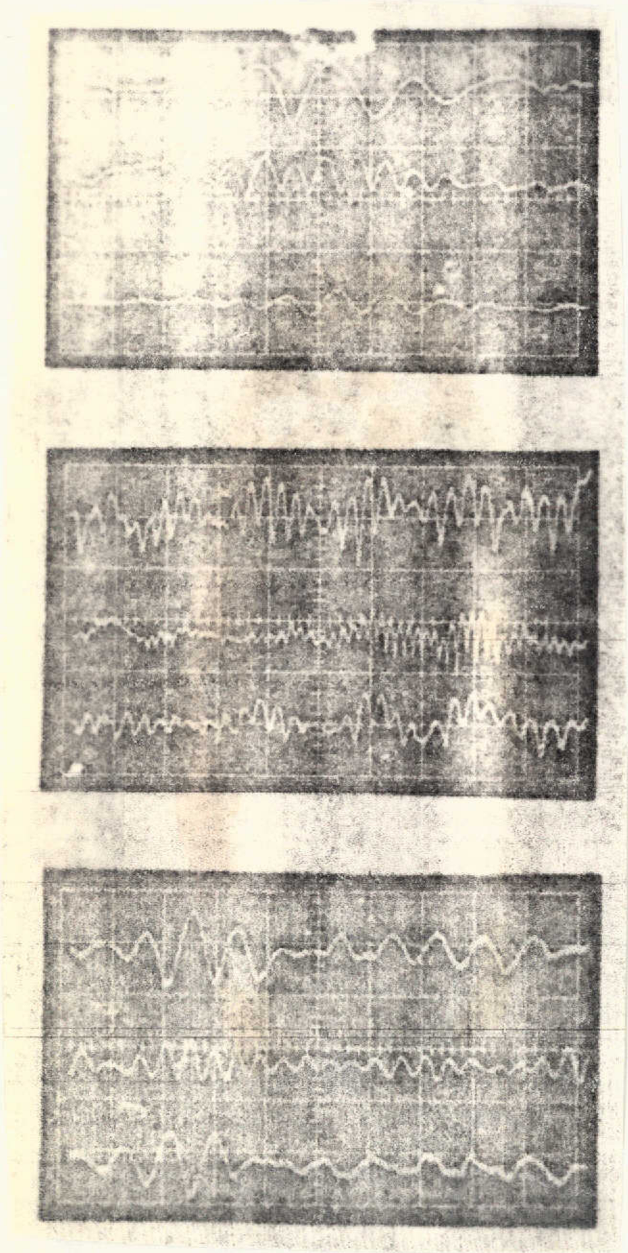

Fig. 15. Oscillograms of Doppler signals for water flowing in a flat tunnel.

is located in a medium with an index of refraction differing appreciably from 1 (e.g. water) or if there are thick tunnel windows in the beam path of the anemometer, between lens L_2 and measurement point O. In this case, we must expect an imaging error which has the same effect as the spherical aberration associated with lenses. On the observation side, the position of measurement point O in an optically denser medium generally requires a correction for angle of observation α. These errors, which will merely be brought to the reader's attention here, can be eliminated by compensating measures.

So far, our studies have been concerned primarily with the method's applicability and the designing of special anemometer configurations. The performance of regular series of measurements and their (electronic) evaluation will be described in another report.

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REFERENCES

1. Rudd, M.J., "The laser anemometer -- a review," Optics and Laser Technology 3(4) (Nov. 1971).

2. Bossel, H.H., Hiller, W.J., and Meier, G.E.A., "Measurement of flow velocities with the optical Doppler effect," Max-Planck-Institut für Strömungsforschung, Göttingen, Report 7/1971.